

LITHO1.0: AN UPDATED CRUST AND LITHOSPHERE MODEL OF THE EARTH (POSTPRINT)

Annual Report 2

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14. ABSTRACT The compilation of extremely large global datasets of group velocity for Rayleigh and Love waves from 10mHz to 40mHz have completed using a cluster analysis technique. The method has been extended to measure phase velocity to complement the group velocity with global data sets of longer period phase data that help to constrain deep lithosphere properties. To model these data, a starting model for the crust at a nominal resolution of 1 degree is required. This has been developed by constructing a map of crustal thickness using data from receiver function and active source experiments where available, and by using CRUST2.0 where other constraints are not available. Particular care has been taken to make sure that the locations of sharp changes in crustal thickness are accurately represented. This map is then used as a template to extend CRUST2.0 to 1 degree nominal resolution and to develop starting maps of all crustal properties. The data is being modeled using two techniques. The first is a linearized inversion about the 3D crustal starting model. Note that it is important to use local eigenfunctions to compute Frechet derivatives due to the extreme variations in crustal structure. Another technique uses a targeted grid search method.					
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LITHO1.0: AN UPDATED CRUST AND LITHOSPHERE MODEL OF THE EARTH

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ABSTRACT

We are developing LITHO1.0: an updated crust and lithosphere model of the Earth. The overall plan is to take the popular CRUST2.0 model—a global model of crustal structure with a relatively poor representation of the uppermost mantle—and improve its nominal resolution to 1 degree and extend the model to include lithospheric structure. The new model, LITHO1.0, will be constrained by many different datasets including extremely large new datasets of relatively short period group velocity data. Other data sets include (but are not limited to) compilations of receiver function constraints and active source studies.

To date, we have completed the compilation of extremely large global datasets of group velocity for Rayleigh and Love waves from 10mHz to 40mHz using a cluster analysis technique. We have also extended the method to measure phase velocity and are complementing the group velocity with global data sets of longer period phase data that help to constrain deep lithosphere properties.

To model these data, we require a starting model for the crust at a nominal resolution of 1 degree. This has been developed by constructing a map of crustal thickness using data from receiver function and active source experiments where available, and by using CRUST2.0 where other constraints are not available. Particular care has been taken to make sure that the locations of sharp changes in crustal thickness are accurately represented. This map is then used as a template to extend CRUST2.0 to 1 degree nominal resolution and to develop starting maps of all crustal properties.

We are currently modeling the data using two techniques. The first is a linearized inversion about the 3D crustal starting model. Note that it is important to use local eigenfunctions to compute Frechet derivatives due to the extreme variations in crustal structure. Another technique uses a targeted grid search method. A preliminary model for the crustal part of the model will be presented.

OBJECTIVES

The main objective is to take the popular CRUST2.0 model - a global model of crustal structure with a relatively poor representation of the uppermost mantle - and improve its nominal resolution to 1 degree and extend the model to include lithospheric structure. The new model, LITHO1.0, will be constrained by many different datasets including extremely large new datasets of relatively short period group velocity data measured with a new technique which are sensitive to lid properties as well as crustal thickness and average crustal properties. Other data sets include (but are not limited to) compilations of receiver function constraints and active source studies.

RESEARCH ACCOMPLISHED

Global Surface Wave Group Velocity and Phase Velocity Data Sets

In a previous paper (Masters et al., 2010), we described a new technique to measure the relative group arrival times of surface wave packets that allows very efficient construction of large data sets. We have applied the technique to all LH data at the Incorporated Research Institutions for Seismology Data Management Center (IRIS DMC) from events larger than $M_s=5.5$ between 1976 and 2007. We also include some BH data from Program for the Array Seismic Studies of the Continental Lithosphere (PASSCAL) experiments in the southern hemisphere and the Portable Observatories for Lithospheric Analysis and Research Investigating Seismicity (POLARIS) network to increase ray coverage. The Rayleigh wave group velocity data set is complete from 10mHz to 40mHz. Similar datasets for Love waves are now complete.

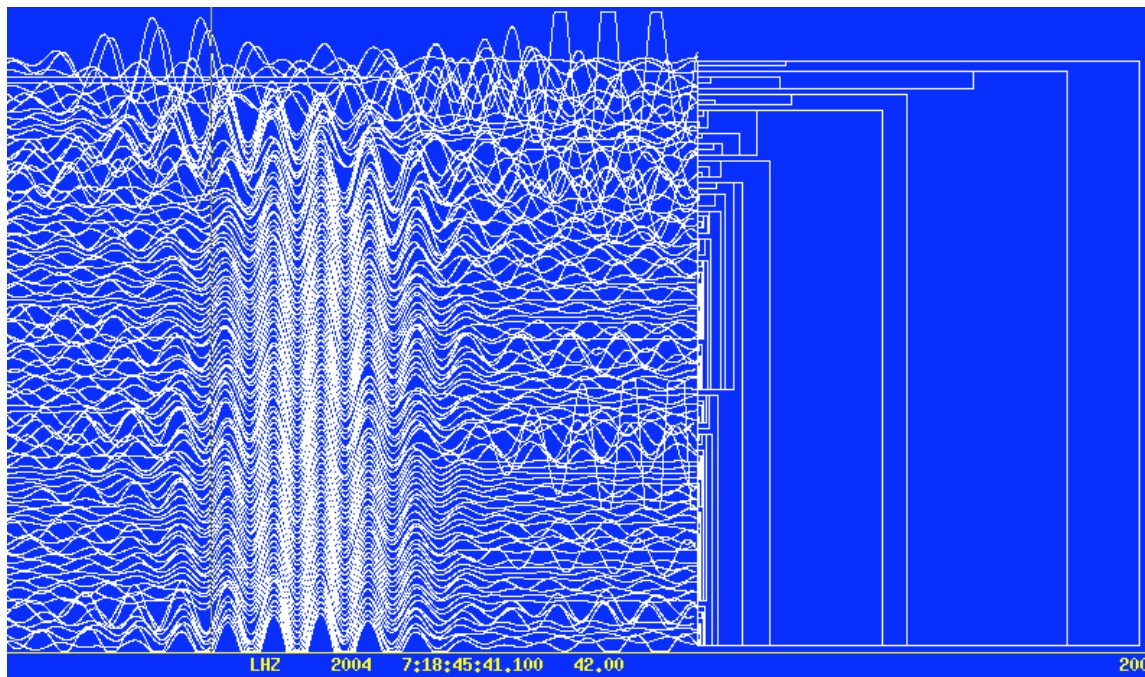


Figure 1. Screen capture showing the processed records after clustering—the cluster tree is on the right. A vertical cursor is used to select the degree of clustering—in this case, there is one useful cluster comprising about 80% of all records. The top records which are noisy form a set of small clusters which are discarded. This example is for a period of 100 seconds.

At very long periods (greater than 100s), group velocity measurements are less reliable than at shorter periods but it is possible to modify the group velocity measurement algorithm to measure phase velocity. When measuring phase, we are no longer working with envelopes so we must be very careful to avoid cycle-skipping. We have found that the following algorithm works. As with the group velocity measurements, we band-pass the records around a frequency of interest but now we also “undisperse” the records using a 1D phase velocity curve so that all records are arriving at a nominal distance of 90 degrees. We correct for source phase and amplitude and we also correct for

the predicted phase shift due to 3D structure by using a nominal phase velocity map. This latter step is important at periods shorter than 100 seconds to avoid cycle skipping but is not necessary at longer periods. The algorithm now follows the group velocity algorithm where we cross-correlate each record to every other for an event then use the cross-correlation coefficients to perform a cluster analysis (Figure 1).

Once clusters of records are identified, we redo the cross-correlation analysis on each cluster to obtain an optimal set of relative arrival times. Note that it is important to limit how much each record can be time-shifted in the cross-correlation analysis. We have found that we must limit time shifts to less than about half a cycle. This is why it is important to pre-shift records using a preliminary phase velocity map. We start the analysis at long periods (200 seconds or 5mHz) then work up in 1mHz increments to 6mHz, 7mHz, etc using the phase velocity map from the previous frequency as a starting phase velocity map for the next frequency. Note that we only have to go through the process of selecting clusters at 5mHz intervals. For intermediate frequencies, we can use the same clusters as determined for the lower frequency analysis. Thus, the 6mHz analysis is done completely automatically using the clusters determined in the 5mHz analysis. We have analyzed Rayleigh waves from 5 to 25mHz and see no difficulty in going to higher frequencies. To date, we have analyzed data from 1988 to 2004 which results in over 310,000 measurements at 10mHz.

The relative arrival times are inverted for a phase velocity map which is then used to convert the data to absolute times. That is, we solve for a mean phase velocity and a time shift for each cluster after correcting the relative arrival time data for the predictions of the preliminary phase velocity map. The absolute times are then used to determine the final phase velocity map. Figure 2 illustrates the phase velocity map derived at a period of 50 seconds from 295,000 phase measurements. Such maps provide an excellent fit to the data with a variance reduction of 95%—but, more importantly, the SMAD of the phase arrival time residuals is only 3.4 seconds which is comparable to our measurement error (Figure 3). We conclude that our final dataset of phase measurements will likely be even larger than those for group velocity and appear to be of higher precision. We are currently in the process of performing a comprehensive error and resolution analysis for the Rayleigh wave datasets.

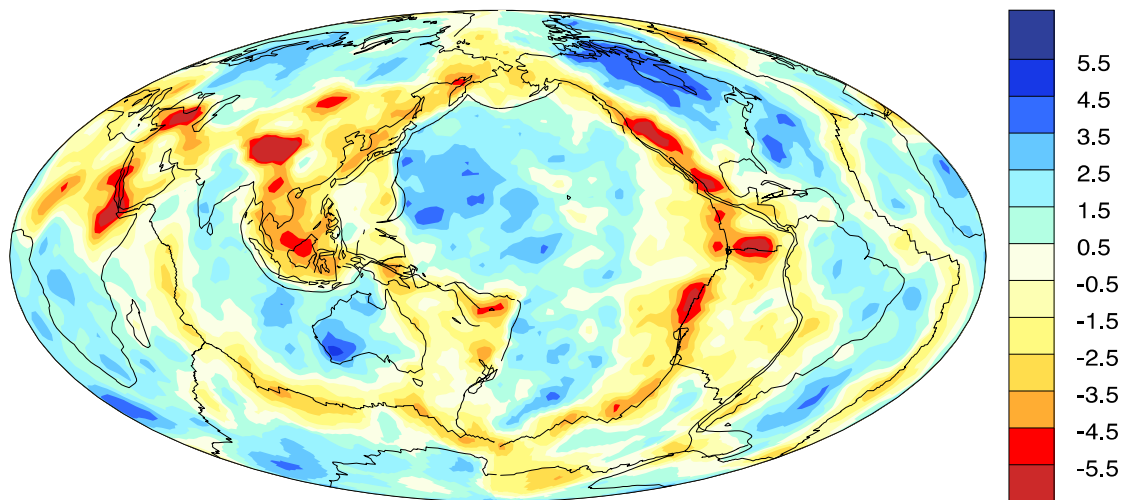


Figure 2. Phase velocity map at 50 seconds, derived from 295,000 phase measurements.

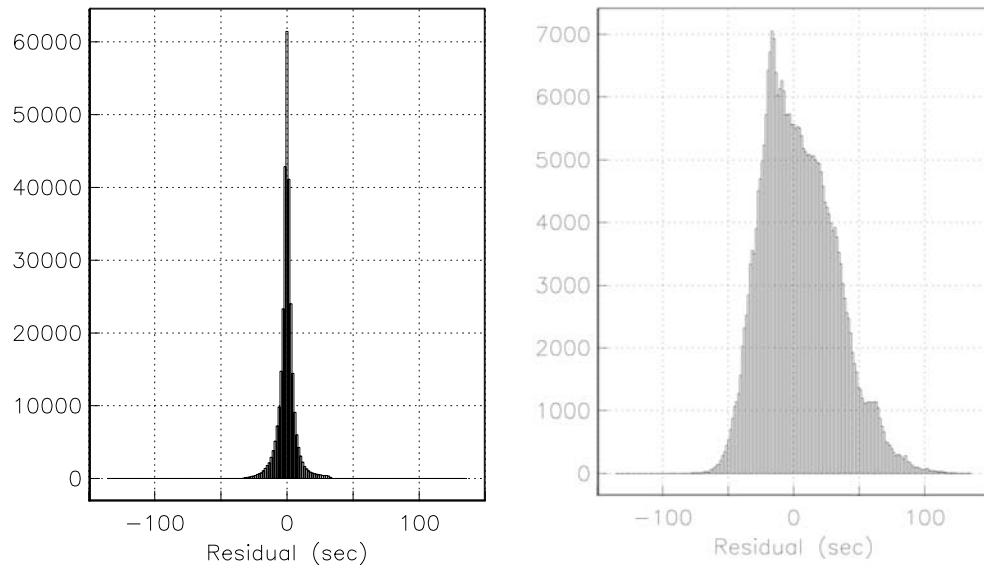


Figure 3. Histograms showing the fit of the phase velocity map at 20mHz to the phase arrival time residuals. There is a 95% variance reduction after inversion (left) and the residual SMAD after fitting is about 3.4 seconds.

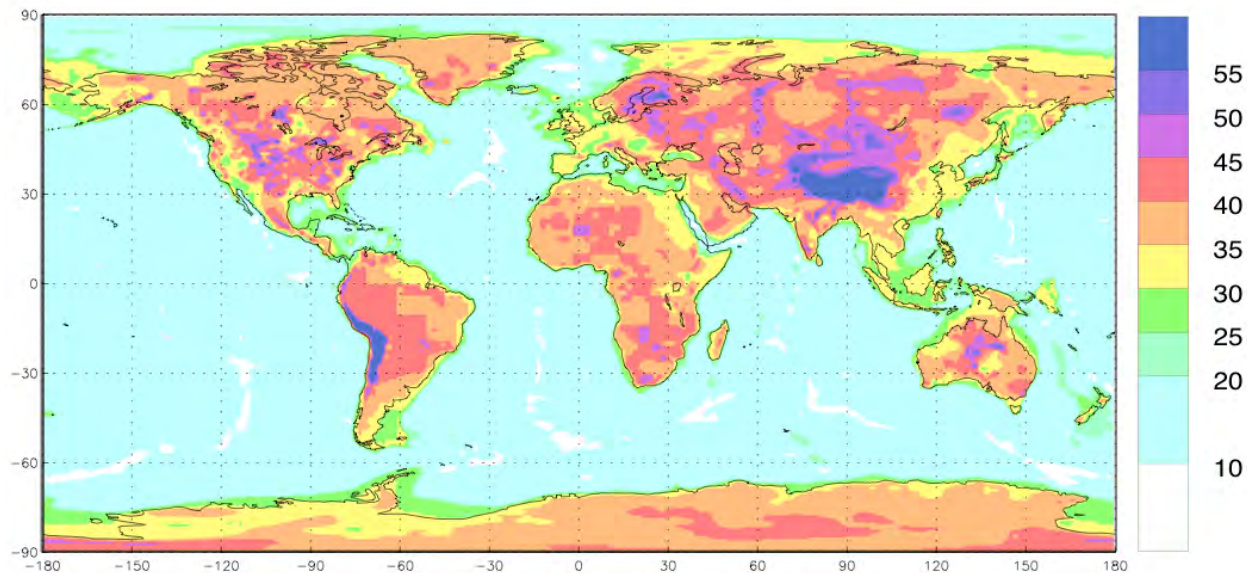


Figure 4. Crustal thickness (including ice and water layers) from a compilation of many studies (see text).

Constructing a Starting Crustal Model

As a precursor to getting the final crust and lithosphere model, we need a new initial crustal model with 1 degree nominal resolution that accurately matches continental shelves, etc. This new model, CRUST1.0, differs from CRUST2.0 (Bassin et al., 2000) in that we use the concept of “crustal type” to specify only the properties of the crystalline crust (Mooney et al., 1998). Topography and bathymetry are taken from ETOPO1 (NOAA’s NGDC: Amante and Eakins, 2009). The ETOPO1 package also includes ice thickness maps for Antarctica and Greenland both of which we included. Information of sediment structure comes from the three-layer sediment model of Laske and Masters (1997) though with modifications to some sediment velocities. We also specify crustal thickness independently of crustal type. The crustal thickness map has been compiled from a literature search of active source

and receiver function studies, and by compiling maps of crustal thickness taken from the literature (Artemieva, 2006, Tesauro et al., 2007, Grad et al., 2008).

Where no other information is available, we have used crustal thickness maps based on gravity (e.g., most of Antarctica) or we have used the crustal thickness of CRUST2.0. The result of this is shown in Figure 4. We have also assembled an initial estimate of the error in the crustal thickness map – typically, normal oceanic crustal thickness is likely to vary by less than 2km, where we have direct observational constraints on continental crustal thickness we use an uncertainty of 3km, where we have a map from the literature we assume an uncertainty of 5km, and everywhere else (including maps based on gravity interpretations) we assume an uncertainty of 10km.

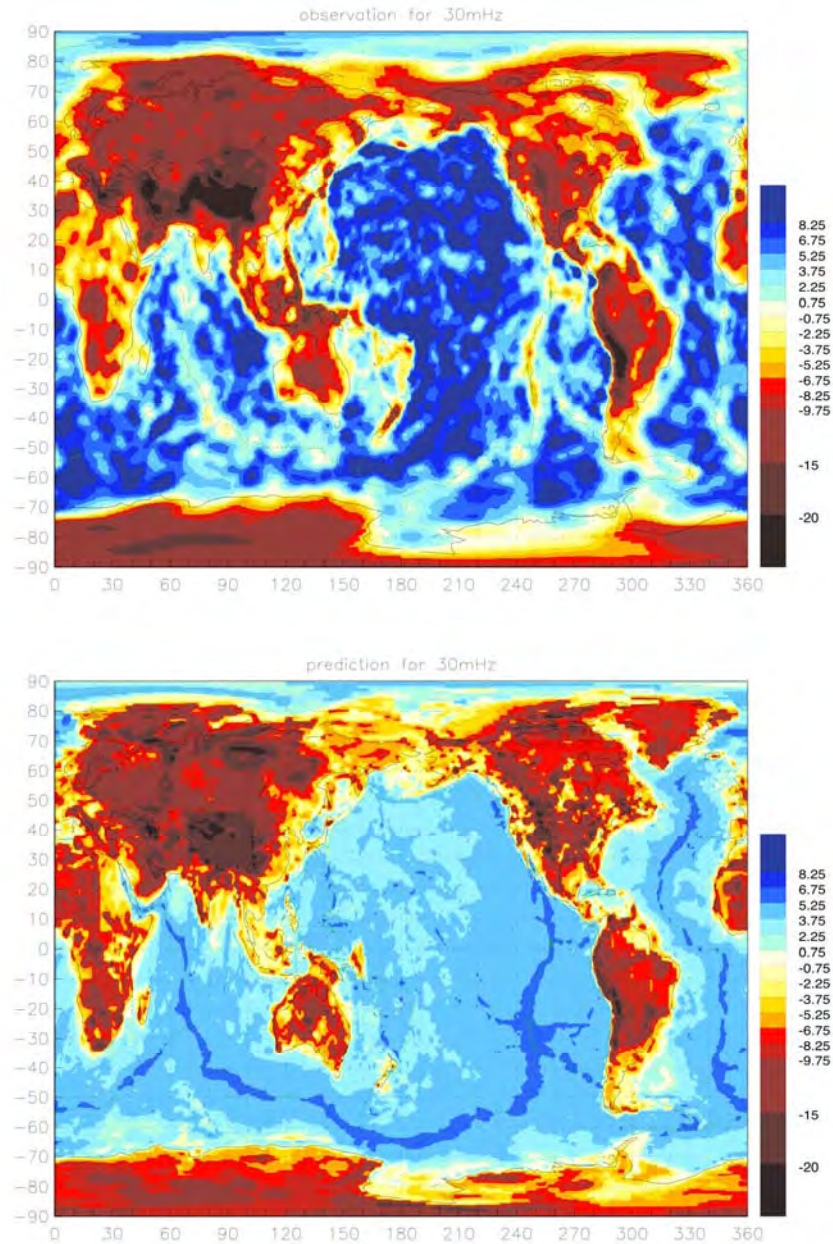


Figure 5. The top shows the observed map of group velocity perturbations (in percent) at a frequency of 30mHz. The bottom shows the prediction of the new crustal model.

The crystalline crust is represented by three layers. We have found that a total of 32 crustal types gives a reasonable representation of the crystalline crust in CRUST1.0 though comparisons with the data suggest some additional crustal types might be appropriate.

It is interesting to compare the predictions of the new starting crustal model with some of the group velocity data sets. Figure 5 (top) shows the observed group velocity map at 30mHz while the bottom shows the predictions of the new crustal model embedded on top of AK135. Note that a separate group velocity calculation is done for each (1 degree) pixel of the maps. There are some interesting discrepancies, e.g., the observed map suggests that we should include a new crustal type for young ocean and back arc basins. There are also some interesting discrepancies where there are intermediate thickness sediment piles such as off the east coast of the United States of America and the west coast of Australia. However, we feel that the starting model is sufficiently close for our purposes. This is verified by comparing spherical harmonic expansions of the two maps (Figure 6).

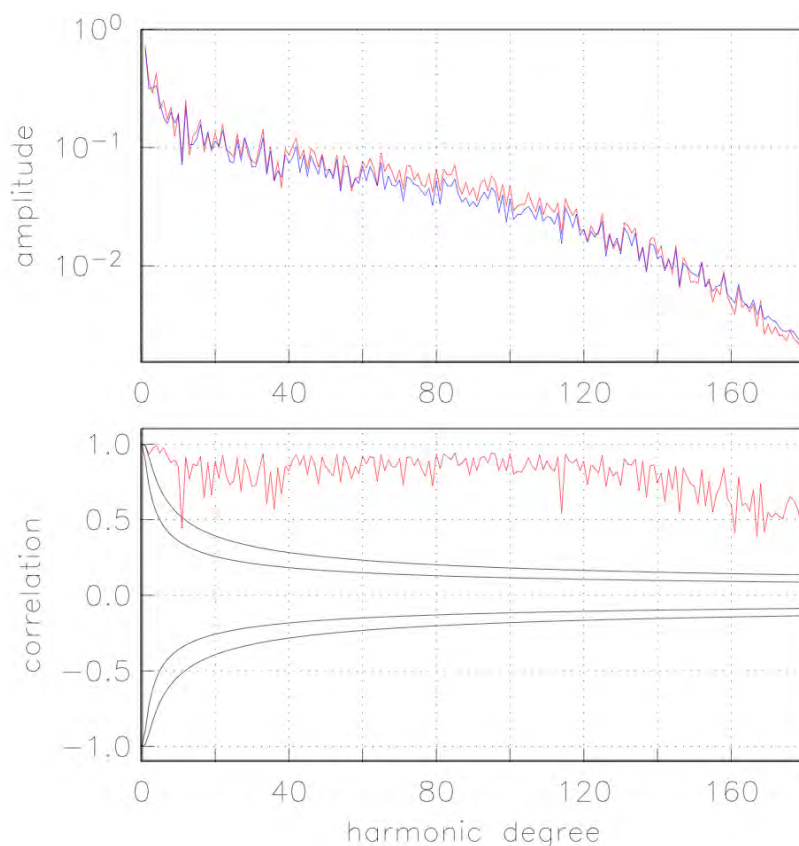


Figure 6. The top shows the amplitude spectra of the group velocity map (red) and the predicted map (blue) as a function of harmonic degree up to degree 180 (appropriate for a 1 degree pixel resolution). The bottom shows the correlation between the two along with the 99% and 90% confidence levels.

Clearly, the amplitude spectra of the two maps are very similar, which suggests that the choice or regularization when making the group velocity map is appropriate. Furthermore, the correlation is extraordinarily high up to the highest harmonic degrees.

Inverting for New Crust and Lithosphere Structure

We plan to use two techniques to obtain improved crustal models. The first technique is computationally efficient but relies on the fact that we have a starting model that is sufficiently close to the final model that an iterative, linearized inversion will work. To do this, we need to compute group velocity kernels for each pixel. We have begun experimentation changing the mean crustal velocity, the moho depth, and the mean lid velocity, keeping all other things fixed. The second technique uses a targeted grid search method that was presented at the SSA meeting this

year (Pasyanos et al., 2011). This technique does not perform any linearization but is computationally much more demanding than the linearization approach.

Using this approach, we use our input datasets of the CRUST1.0 crustal profile, crustal thickness, sediment thickness, and the upper mantle model LLNL-G3D (Myers et al., 2011; Simmons et al., 2011) to create an initial model. We then perturb a number of model parameters (crustal velocities, mantle velocities, crustal thickness, lid thickness) and create a suite of models. The models are then tested to find the model that best fits the surface wave data. For example, Figure 7 shows an example of a grid search for a node in Siberia. The gray lines show the dispersion predictions from the suite of models, where red lines indicate better fitting models. The green line, which produces the best fit to the data indicated by the green symbols, is shown in the depth profile to the right. This particular node required a slower mantle with a thick lid.

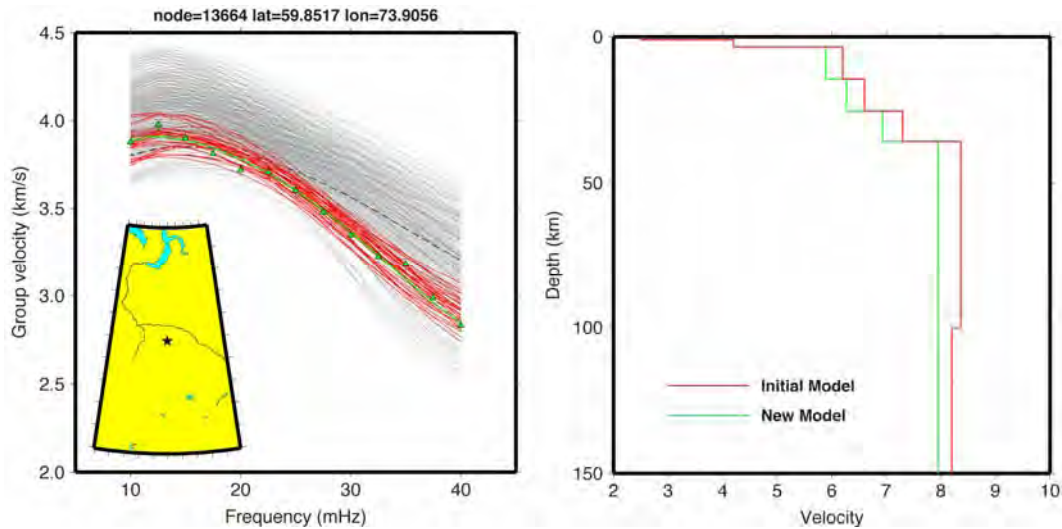


Figure 7. Example of targeted grid search method for a node in Siberia. The left panel shows dispersion for the suite of models, while the right panel shows initial and new model.

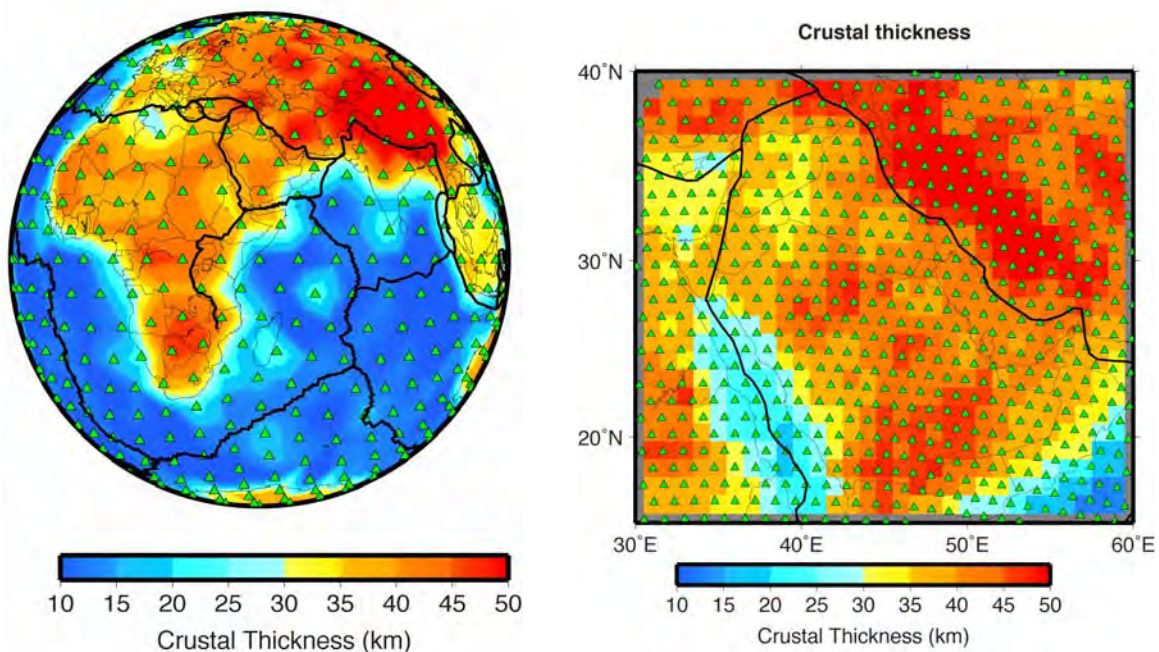


Figure 8. Crustal thickness maps of a global, low-resolution model and a regional, high-resolution model.

We are now in a position to assemble the results from individual nodes to start and construct the LITHO1.0 model. Figure 8 shows a global, low-resolution model where the inversion were performed at tessellated nodes with about 8° spacing alongside a high-resolution regional model of the Middle East where the node spacing is about 1°.

CONCLUSIONS AND RECOMMENDATIONS

We have completed the construction of a new large global dataset of Rayleigh and Love wave group arrival times using a new efficient measurement technique and have evaluated the data by constructing group velocity maps using simple ray theory. We have extended the technique to measure phase and the new datasets of phase measurements are likely to be as large and more precise than the group velocity data sets.

We have constructed a new crustal model with 1 degree nominal resolution as a starting point for inversion. This model predicts group velocity perturbations with very similar spectral characteristics to the data though detailed comparisons suggests further improvement of the starting model by adding a few new crustal types and by adjusting some sediment velocities.

We are now in a position to begin detailed modeling of the data sets for the new crust and lithosphere model.

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